Holz als Roh- und Werkstoff (2006) 64: 235–242
DOI 10.1007/s00107-005-0059-7

ORIGINALARBEITEN · ORIGINALS

Magnus Bäckström · Robert Kliger

Restraining moisture-related twist in timber structures

Published online: 23 December 2005

Abstract Timber changes its shape at varying moisture content levels. In most pieces of timber, this causes distortion, such as twist, spring, bow and cup. Twist is one of the most severe distortion modes and is reversible at varying moisture contents. Restraining a stud from twisting in built-in conditions results in additional forces in the structure. This paper presents a method for measuring the torsional moment while restraining the twist during drying in in-service conditions. The results include the development of torsional moment and the moisture content versus time, as well as the final torsional moment and the corresponding free twist. The magnitude of the torsional moment in studs results in forces affecting the surrounding structure which can then be restrained in an appropriate manner by fasteners. The development of torsional moment versus time demonstrates the importance of controlling the moisture content and the importance of a rapid building process when there is a risk of fast drying. The measured torsional moment was correlated to several measured material properties. However, a good correlation was only found between torsional moment and free twist.

Verhinderung feuchtebedingter Verdrehungen in Holzkonstruktionen

Zusammenfassung Holzfeuchteänderungen führen bei Holz zu Formänderungen wie zum Beispiel Verdrehung, Längs- und Querkrümmung sowie Schüsselung. Eine der schlimmsten Verformungen ist die Verdrehung, die bei wechselnder Holzfeuchte reversibel ist. Das Geradebiegen verdrehter Holzständer beim Einbau führt zu einer zusätzlichen Beanspruchung der Konstruktion. In diesem Manuskript wird eine Methode vorgestellt, zur Messung des Torsionsmoments infolge einer behinderten Verdrehung während der Trocknung unter Praxisbedingungen. Die Ergebnisse beinhalten den zeitlichen Verlauf des Torsionsmoments und der Holzfeuchte als auch das maximale Torsionsmoment und die entsprechende unbehinderte Verdrehung. Das Torsionsmoment in den Holzständern führt zu Kräften, die auf die umgebende Konstruktion wirken, und die dann in geeigneter Form über Verbindungsmitteln aufgenommen werden können. Der zeitliche Verlauf des Torsionsmoments zeigt, wie wichtig es ist, die Holzfeuchte zu kontrollieren und das Holz schnell zu verarbeiten, wenn eine schnelle Trocknung zu befürchten ist. Das gemessene Torsionsmoment wurde mit verschiedenen gemessenen Materialeigenschaften korreliert. Eine gute Korrelation ergab sich jedoch nur zwischen Torsionsmoment und unbehinderter Verdrehung.

M. Bäckström · R. Kliger (✉)
Division of Structural Engineering – Steel and Timber Structures Chalmers, University of Technology, 412 96 Göteborg, Sweden
E-mail: Robert.kliger@sem.chalmers.se

1 Introduction

Timber changes its shape in terms of twist, spring, bow and cup (distortion) at varying moisture content levels. The most severe distortion modes for structural timber are spring and twist. This paper focuses on moisture-related twist in studs hanging freely and measurements of torsional moment (M_T), which prevents additional twist in studs during additional drying in in-service conditions in a structure.

2 Background

Timber that is prone to twist is a problem for the building industry and sometimes even when this timber is built into a structure. Twist increases when the moisture content (MC) decreases and vice versa. In Scandinavia, structures such as houses dry from about 18% MC when assembled to about 8% MC in in-service conditions. However, the timber is restrained by the built-in conditions, causing forces to develop in the structure. Suitable erection methods and satisfactory fasteners are needed to prevent the studs that are prone to twist deforming the structure, causing chinks or cracks on interior surfaces such as wall panels. The question then arises of how strong the fasteners should be and which requirements should be set for the strength and stiffness of the cladding of the wall panels. To answer this question, it is necessary to know how large the force on the fasteners and cladding will be. This leads to the need to find the M_T that occurs

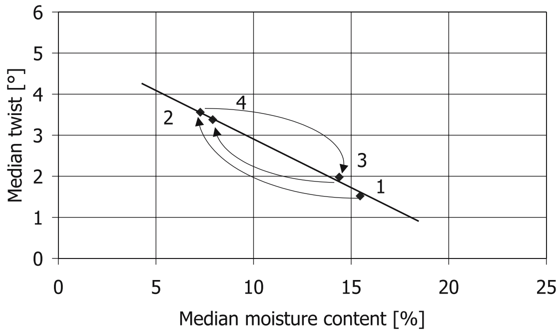


Fig. 1 Reversibility of twist, free-distortion history. Median results on four measurement occasions from 240 studs measuring 45×70 mm (Johansson et al. 2001)

Abb. 1 Reversibilität von Verdrehung. Mittelwerte von 240 Kanthölzern 45×70 mm bei vier Feuchtezuständen (Johansson et al. 2001)

when a stud that is prone to twist is kept straight during drying in in-service conditions. Another question is if and how this M_T is related to other material properties. The timber structures must fulfil the requirements set for structures when it comes to shape stability, even when timber that is naturally prone to twist but has been straightened in a kiln is used. With a knowledge of the magnitude of the M_T for material that is prone to twist, the strength capacity of the fasteners and the strength and stiffness of the materials in the surrounding structure, it would be possible to predict the expected distortion in the structure and thereby make appropriate arrangements for its limitation.

Previous tests on studs have demonstrated good reversibility in terms of MC-free distortion, especially twist, see Johansson et al. (2001) and Kliger et al. (2003). The free distortion was accomplished by suspending the studs vertically without any restraint. The studs in these tests measured $45 \times 70 \times 2500$ mm^3 and their distortion was measured on four occasions. These measurements were made to see how reversible the distortion was during moisture cycling, cf. Fig. 1. These climate variations were made to simulate changes in MC to which timber can be exposed on its way from the sawmill to the finished building.

This knowledge of the reversibility of free twist was used in the tests presented in this paper. It also makes it possible to correlate the M_T to the measured free twist. Two main groups of studs, kiln dried in restraint and kiln dried without restraint, were used.

The M_T on studs has been measured by Mackay (1973), Northway (1981), Shmulsky and Erickson (2004) and Salin (2004), among others. These papers focused on the restraint in the kiln-drying process when drying from "green" condition by increasing the temperature and air velocity. However, Mackay (1973) presented some samples that were cycled between 15% MC and 5% MC.

3 Objectives

The main objectives of this paper are: 1) to show how the torsional moment (M_T) in studs prone to twist was measured, 2) to show the development of the M_T during drying in in-service conditions from a high MC (about 18% MC) to a low MC (about 8% MC) and 3) to show the magnitude of the final M_T in relation to other material parameters and to the measured twist.

4 Material and methods

4.1 Test material

A total of twelve studs were used to measure the torsional moment (M_T). The studs were tested in four series, each comprising three studs. The studs measuring $50 \times 100 \times 2500$ mm^3 had a well-known restrained-free-distortion history, measuring twist at different MC, as shown in Fig. 1. The studs were chosen as they had relatively large twist compared with spring and bow. Nine of the studs came from a kiln-drying test performed by the Norwegian Teknologisk Institute. The kiln drying was performed with a normal-temperature kiln schedule but with different top loads. Seven of the studs were kiln dried with a top load (ET) of 1300 kg/m^2, while two of the studs were dried without any load (EU). Three of the studs came from a kiln-drying test performed by the VTT. The test at the VTT was conducted to compare high-temperature drying with low-temperature drying. For the tests of M_T, two studs dried at high temperature (HT) (≈ 105 °C) and one stud dried at low temperature (LT) (≈ 70 °C) were used. These studs were kiln dried without any top load.

For each test series, a fourth stud of the same material was chosen as a control for measurements of MC. Before the tests started, the studs had been conditioned for at least three months. For the first two test series, the conditioning was performed at 85% relative humidity (RH), while for the last two test series the conditioning was performed at 75% RH. The temperature was 22 °C during the conditioning process.

4.2 Measurement of material parameters

Several material parameters were measured to identify properties in the material and relate them to the final M_T. Unless otherwise stated, all the measurements presented here were made at Chalmers University of Technology. In Table 1, the material properties measured on the studs are presented. The density, ρ, was based on the weight of the stud on the first dry measurement occasion (~8% MC) and the nominal measurements of ($h \times b \times L$) $50 \times 100 \times$ 2500 mm. The spiral grain angle, *SGA*, was measured using the scribe method on the tangential face of the stud and was the average of three measurements along the length of the stud. The modulus of elasticity, E, was evaluated from the first axial eigenfrequency mode, f_{a_1}, obtained from dynamic tests and calculated from Eq. 3. The modulus of shear, G_{dyn}, was evaluated from the first torsional eigenfrequency mode, f_{t_1}, obtained from dynamic tests and calculated from Eq. 4 (Perstorper 1999). The measurements of the eigenfrequencies were performed at 30% RH, which corresponds to 8% MC. The I_p was the polar moment of inertia calculated from Eq. 1. The K_v was the cross-section warping modulus calculated from Eq. 2 and the

factor η_2 depends on the relationship between b and h (in this case 0.229).

$$I_p = I_x + I_y = \frac{b \cdot h^3}{12} + \frac{h \cdot b^3}{12} \quad (1)$$

$$K_v = \eta_2 \cdot b \cdot h^3 \quad (2)$$

$$E = (f_{a\_1} \cdot 2 \cdot L)^2 \cdot \rho \quad (3)$$

$$G_{dyn} = (f_{t\_1} \cdot 2 \cdot L)^2 \cdot \frac{\rho \cdot I_p}{K_v} \quad (4)$$

4.3 Measurement of size and distribution of moisture content

The MCs during the tests were checked using the dry-weight method. The control studs were used to check the MC. The moisture content of the restrained stud was assumed to be the same as that of the control stud. The checks were made at weekly intervals, but they were more frequent during the first two weeks. The checking of the MC resulted in a good knowledge of the MC and its distribution over the cross-section during the ongoing test series of the torsional restraint of the studs, cf. Fig. 4.

Table 1 Material properties measured on the studs used in this paper. Density ρ , on the first dry measurement occasion, *SGA* (spiral grain angle), E (modulus of elasticity) and G_{dyn} (modulus of shear)
Tabelle 1 Gemessene Materialeigenschaften der untersuchten Holzständer. Dichte ρ, im trockenen Zustand bei Versuchsbeginn, *SGA* (Faserwinkel), E (Elastizitätsmodul) und G (Schubmodul)

Stud no	Test series no	ρ [kg/m^3]	*SGA* [°]	E [MPa]	G_{dyn} [MPa]
EU26		553	1.7	15362	1037
ET16	1	515	3.1	13904	919
ET26		522	1.6	13799	885
ET2		382	1.7	9508	716
ET13	2	468	2.1	13556	834
EU34		552	1.8	15901	1096
HT11		429	3.2	12917	777
HT44	3	481	1.6	14227	925
LT27		394	1.8	10499	767
ET22		481	2.1	14486	770
ET24	4	512	2.8	14362	913
ET44		463	1.5	14394	781

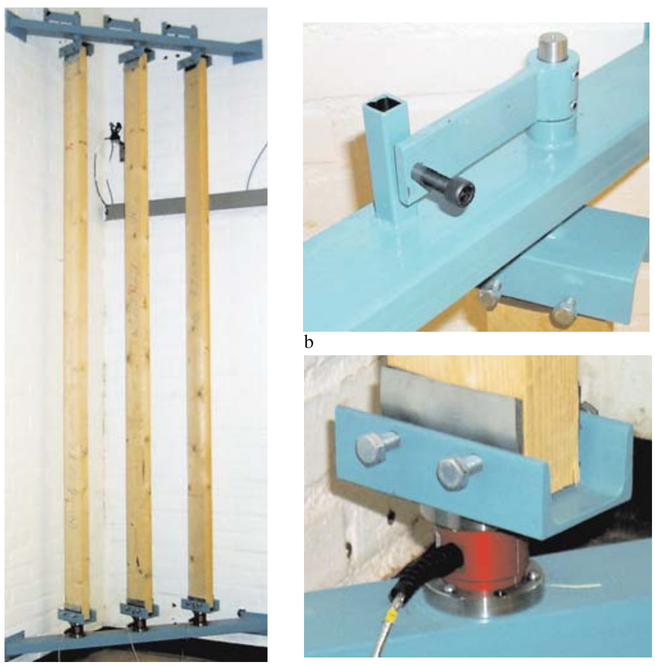
1	7	13	19	25	31	37	43	49	55
2	8	14	20	26	32	38	44	50	56
3	9	15	21	27	33	39	45	51	57
4	10	16	22	28	34	40	46	52	58
5	11	17	23	29	35	41	47	53	59
6	12	18	24	30	36	42	48	54	60

Fig. 2 Numbering of the 60 pieces in the cross-section. The outer part comprised the edge parts of the profile, i.e. nos 1–6, 1, 7, 13 ... 55, 6, 12, 18 ... 60, 55–60. The other pieces were the inner part
Abb. 2 Unterteilung der Holzquerschnitte in 60 Elemente. Den äußeren Teil bilden die Randelemente, d.h. 1–6, 1, 7, 13 ... 55, 6, 12, 18 ... 60, 55–60. Die restlichen Elemente bilden den Innenteil

To produce a moisture content profile from the control stud, a slice of about 20 mm was cut off. The slice was cut consecutively about 50–100 mm from the end of the stud. The slice was divided into 60 almost equal square-shaped pieces, cf. Fig. 2. They were weighed as quickly as possible (within five minutes) on a balance (Mettler, precision 1/1000th of a gram), after which the pieces were dried in an oven at 103 °C for about 24 hours and then weighed again. The results produced the average moisture content and the distribution of the moisture content. Between the occasions on which a new slice was cut, the end of the stud was sealed with silicon in order to prevent the moisture forcing its way out of or into a stud from the end in the grain direction.

4.4 Measurement of torsional moment

The test jig was made of steel and consisted of two parts, one lower clamping section and one upper clamping section, which was able to rotate, see Fig. 3. The upper part was fixed with a clamp connected to an axis with a screw. The screw made it possible to fix each of the tested studs at the start of each test series to compensate for the small existing twist at the high MC (about 18% MC). The bottom section was fixed with a clamp connected to the frame via the torsional moment (M_T) device (Dr. Steiger Mohilo®, 0150D). The registration interval was very short, 20 seconds, at the beginning of the tests, but it was gradually extended. After about four days, the interval was set at four hours for the rest of each test period.



a b c

Fig. 3a–c Measuring the torsional moment of a stud. **a** Overview of the test set-up. **b** Detail of the top section. **c** Detail of the bottom section which includes the device for measuring torsional moment
Abb. 3a–c Torsionsmomentmessung von Holzständern. **a** Gesamtansicht der Versuchsanordnung **b** Detail der oberen Halterung. **c** Detail der unteren Halterung mit dem System zur Messung des Torsionsmoments

The RH in the dry conditioning test chamber was between 30% and 35% and the temperature was about 22 °C. The RH and the temperature in the test chamber were registered with a logger (Testo®, 175-H2).

5 Results

5.1 Development of torsional moment

The results of the tests of torsional restraint revealed that the M_T increased when the MC decreased. Figure 4 shows the continuous development of the M_T and the MC for the second test series. The curves for the development of M_T and MC for the other three test series have a similar appearance. The curves show that, within a week, 50% of the final M_T was reached. The MC development during the tests can be followed by the descending curve with square-shaped points. The MC profile is illustrated in four points, two at the top and two at the bottom of Fig. 4. The upper-left MC profile shows that the stud was fairly well conditioned at the start of the test. The upper-right MC profile shows that, after one day, the drying mainly took place in the surface of the stud. The lower-left MC profile shows that, after about three weeks, the surface parts of the cross-section had more or less reached equilibrium with the surrounding climate, but there were still higher MCs in the middle of the stud. The

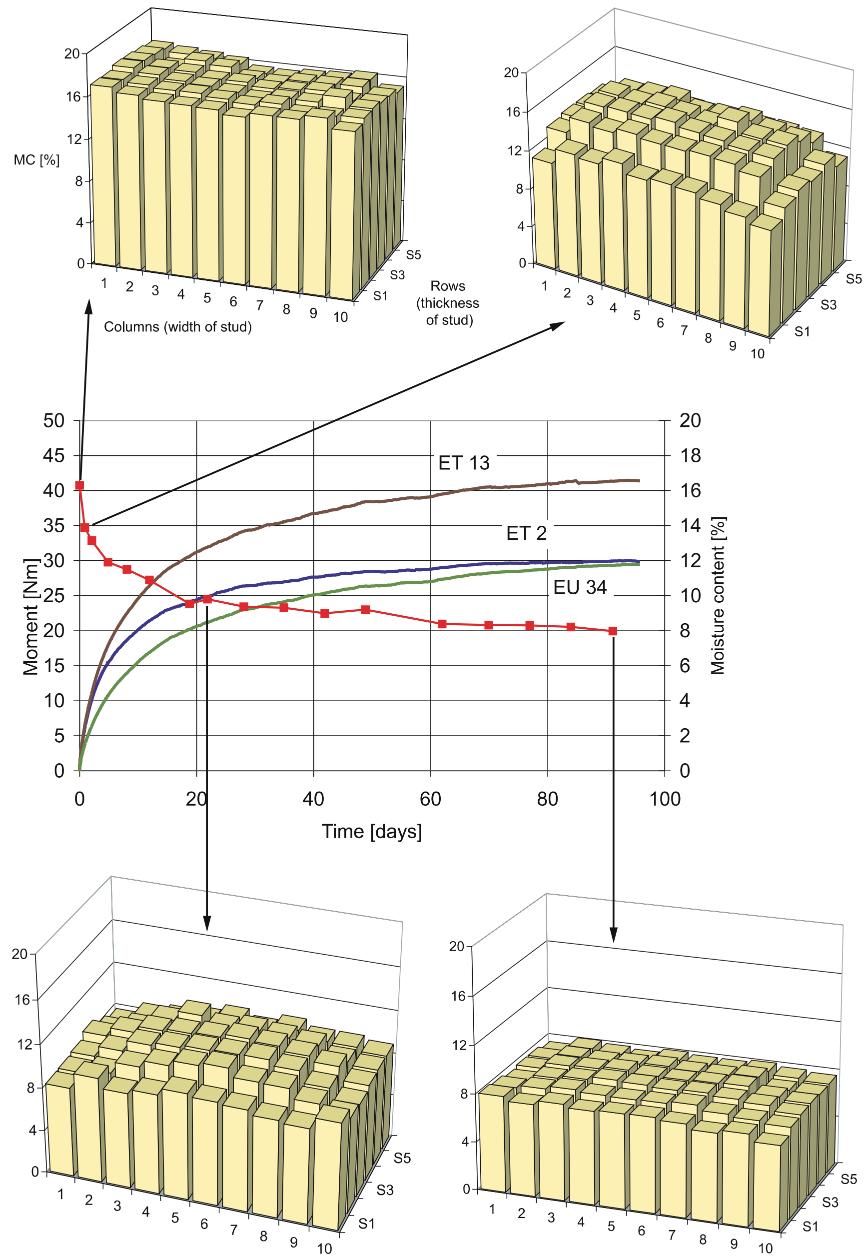


Fig. 4 The development of the torsional moment (M_T) for three studs and the associated moisture content (MC) on four occasions
Abb. 4 Zeitlicher Verlauf des Torsionsmoments (M_T) von drei Holzständern und die dazugehörigen Holzfeuchten (MC) an vier Zeitpunkten

lower-right MC profile shows the equilibrium MC at the end of the test.

It appears that, when the MC in the outer part of the cross-section of a stud has reached the equilibrium MC with the surrounding climate, the increase in M_T has more or less reached its final (maximum) value. An analogy to the mechanics means that the outer parts have a greater impact on the torsional stiffness than the inner parts.

Tables 2–5 show the M_T and the percentage of M_T compared with the MC and the percentage of drying related to time for five different occasions. After 80 days, the studs had reached equilibrium MC, the M_T no longer increased and the tests were aborted, see Fig. 4.

The relative rate of development of M_T for studs EU26, ET16 and ET26 was about the same as the rate for relative drying after two days. However, after five and eight days, the relative development of M_T was slightly faster than the relative drying.

The relative rate of development of M_T for studs ET2, ET13 and EU34 was slower than the rate for the relative drying after two and five days. However, after eight days, the relative development of M_T was about the same as the relative drying, except for untreated stud EU34 that had a slower relative development of M_T than the relative drying.

The relative rate of development of M_T for studs HT111, HT144 and LT127 was slightly faster than the rate for the relative drying after two, five and eight days. This applied to all three studs, regardless of treatment in the kiln, high- or low-temperature drying.

The relative rate of development of M_T for studs ET22, ET24 and ET44 was slightly faster than the rate for relative drying after two, five and eight days.

The results show that, for the majority of the studs, the development of M_T is faster than the decrease in average MC.

Table 2 Torsional moment (M_T) and M_T as a percentage of the final M_T, mean moisture content (MC) and percentage of drying related to time for the first test series

Tabelle 2 Absolutes und auf den Maximalwert bezogenes Torsionsmoment (M_T), mittlere Holzfeuchte (MC) und Trocknungsrate für die erste Versuchsserie

Stud no			EU26		ET16		ET26	
Time [days]	MC [%]	Dry. rate [%]	M_T [Nm]	M_T [%]	M_T [Nm]	M_T [%]	M_T [Nm]	M_T [%]
0	19.0	0	0	0	0	0	0	0
2	15.9	32	2.9	29	7.5	34	3.4	31
5	14.4	48	5.4	55	11.5	52	5.6	51
8	13.6	56	7.0	70	13.9	63	6.3	58
Approx. 80	9.4	100	9.9	100	22.0	100	10.9	100

Table 3 Torsional moment (M_T) and M_T as a percentage of the final M_T, mean moisture content (MC) and percentage of drying related to time for the second test series

Tabelle 3 Absolutes und auf den Maximalwert bezogenes Torsionsmoment (M_T), mittlere Holzfeuchte (MC) und Trocknungsrate für die zweite Versuchsserie

Stud no			ET2		ET13		EU34	
Time [days]	MC [%]	Dry. rate [%]	M_T [Nm]	M_T [%]	M_T [Nm]	M_T [%]	M_T [Nm]	M_T [%]
0	16.3	0	0	0	0	0	0	0
2	13.2	38	9.9	33	10.9	27	6.2	22
5	11.9	54	15.5	52	18.2	44	10.9	38
8	11.5	59	18.5	62	22.4	55	14.4	50
Approx. 80	8.2	100	29.7	100	41.0	100	28.8	100

Table 4 Torsional moment (M_T) and M_T as a percentage of the final M_T, mean moisture content (MC) and percentage of drying related to time for the third test series. In this test series, two control studs were used for MC measurements, one for the high-temperature material and one for the low-temperature material

Tabelle 4 Absolutes und auf den Maximalwert bezogenes Torsionsmoment (M_T), mittlere Holzfeuchte (MC) und Trocknungsrate für die dritte Versuchsserie. In dieser Versuchsserie wurden zwei Vergleichsproben zur Messung der Holzfeuchte verwendet. Eine für die hochtemperaturgetrockneten Proben und eine für die bei normaler Temperatur getrockneten Proben

Stud no			HT111		HT144				LT127	
	MC for HT						MC for LT			
Time [days]	MC [%]	Dry. rate [%]	M_T [Nm]	M_T [%]	M_T [Nm]	M_T [%]	MC [%]	Dry. rate [%]	M_T [Nm]	M_T [%]
0	13.1	0	0	0	0	0	13.9	0	0	0
2	12.2	18	4.4	24	5.4	19	12.8	20	6.2	30
5	11.6	30	7.7	41	10.2	36	11.9	36	10.0	49
8	11.0	42	9.6	51	13.3	47	11.1	50	12.4	60
Approx. 80	8.1	100	18.7	100	28.4	100	8.3	100	20.6	100

Table 5 Torsional moment (M_T) and M_T as a percentage of the final M_T, mean moisture content (MC) and percentage of drying related to time for the fourth test series

Tabelle 5 Absolutes und auf den Maximalwert bezogenes Torsionsmoment (M_T), mittlere Holzfeuchte (MC) und Trocknungsrate für die vierte Versuchsserie

Stud no			ET22		ET24		ET44	
Time [*days*]	MC [%]	Dry. rate [%]	M_T [Nm]	M_T [%]	M_T [Nm]	M_T [%]	M_T [Nm]	M_T [%]
0	14.2	0	0	0	0	0	0	0
2	12.9	24	5.2	31	5.4	26	5.7	25
5	12.2	36	8.1	49	8.7	42	9.7	42
8	11.7	46	9.9	59	11.0	54	12.3	54
Approx. 80	8.7	100	16.7	100	20.5	100	22.7	100

5.2 Relationship between restrained torsional moment and free twist

The M_T developed because the free twist was prevented from developing by the restraints. The free twist in the studs was measured either before or after the test of M_T. For all the studs, the twist was measured on eight occasions, at the sawmill and before and after the test of torsional restraint. The numbers 1–8 in Fig. 5 refer to different measurement occasions. A measurement occasion represents an occasion on which twist and MC were measured, cf. also Fig. 1. The ΔTW was defined as the difference in free twist for the same change in moisture content as for M_T. The ΔTW is presented in degrees [°] for a length of 2 m. The free twist in the studs was measured in a specially-constructed device (Perstorper et al. 2001). The magnitude of the free twist

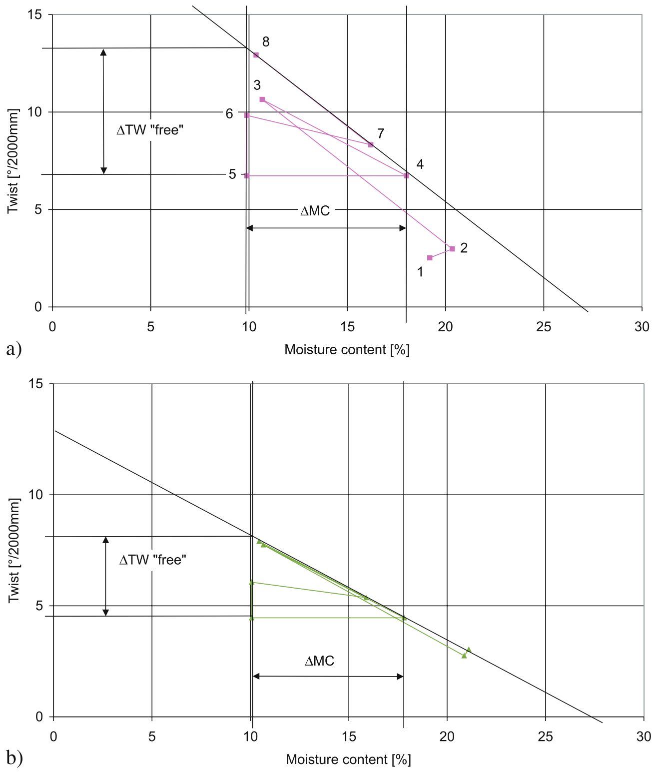


Fig. 5 Typical twist-moisture content relationship for the tested studs. The numbers 1–8 refer to different measurement occasions. No 1 was performed at the sawmill, no 2 after first wet conditioning hanging freely, no 3 after conditioning hanging freely in a dry climate, no 4 after conditioning hanging freely in a humid climate, no 5 in a jig in restraint after three months' conditioning in a dry climate, no 6 free, within half an hour after removal from the restraint, no 7 after conditioning hanging freely in a humid climate, no 8 after conditioning hanging freely in a dry climate.

a) Typical twist versus moisture-content relationship for a stud dried in a kiln with a top load (stud ET 13)

b) Typical twist versus moisture-content relationship for a stud dried in a kiln without a top load (stud EU34)

Abb. 5 Typischer Zusammenhang zwischen Holzfeuchte von Holzständern. Die Ziffern 1–8 bezeichnen verschiedene Messzeitpunkte. 1: im Sägewerk, 2: im extremen Feuchtklima, freihängend, 3: im Trockenklima, freihängend, 4: im Feuchtklima, freihängend, 5: eingespannt, nach drei Monaten im Trockenklima, 6: dreißig Minuten nach Lösen der Einspannung, 7: im Feuchtklima, freihängend, 8: im Trockenklima, freihängend

a) Holzständer, technisch getrocknet, mit Auflast (Holzständer ET13)

b) Holzständer, technisch getrocknet, ohne Auflast (Holzständer EU34)

was a value of the natural propensity of the material to twist. The ΔTW was based on measurements of twist in the studs suspended vertically (free) before or after the measurement of torsional moment. Figure 5 shows the twist-moisture content history for two of the studs where the free twist was established after the test of torsional moment.

For the first six studs, the ΔTW was based on the measurements in the first wet-dry cycle after the measurement of the M_T, i.e. the line between points 7 and 8 in Fig. 5. This means that the twist-MC relationship for the restrained case was obtained first and the measurement of the free twist-MC relationship was obtained after a relaxation period. The ΔTW was extrapolated and/or interpolated to the same difference in moisture content, ΔMC, as that registered during measurement of the M_T, the line between points 4 and 5 in Fig. 5.

For the last six studs, the ΔTW was based on the measurements in the last wet-dry cycle before the measurement of M_T. The relationship between the ΔTW and ΔMC was found in a similar way as for the first six studs.

The studs dried in a kiln with a top load (based on seven studs) appear to display an increase in ΔTW in each moisture cycle after kiln drying, cf. Fig. 5a from points 2 to 4 and from points 6 to 8, for example. The studs dried in a kiln without a top load (based on five studs) show good reversibility regarding ΔTW versus MC, cf. Fig. 5b. These studs appear to find their way back to their previous path in the twist-MC relationship within the next MC cycle.

The average registered final M_T was 22.8 Nm, with a range in data from 9.9 Nm to 41.4 Nm. The corresponding free twist (ΔTW) in the studs varied between 2.0 %/2 m and 6.6 %/2 m. The stud with the highest registered final M_T was the one with the highest free twist, but the same could not be said of the stud with the lowest registered final M_T. Figure 6 shows the relationship between the measured final M_T and ΔTW. For the twelve tested studs, 61% ($R^2 = 0.61$) of the variation in final M_T depends on the ΔTW. The three test series with only low-temperature kiln-dried studs, test series 1, 2 and 4, display a fairly linear relationship with an even higher degree of explanation for each individual test series. The test series including the two high-temperature studs does not show such a good relationship. One of the high-temperature-dried studs displayed a large M_T compared with the ΔTW. It does not appear to matter whether the ΔTW was established after, series 1 and 2, or before, series 3 and 4, the measurement of M_T in restraint.

5.3 Relationship between torsional moment and material parameters

One purpose within this project was to find a relationship between some easily-measured material parameters and M_T that

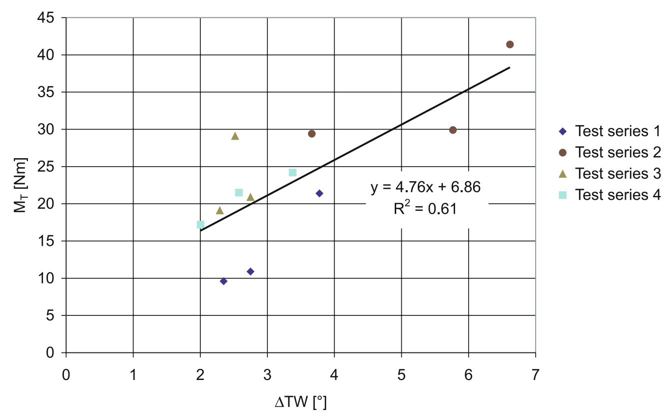


Fig. 6 The relationship between the final torsional moment and the corresponding difference in twist for the four tests

Abb. 6 Zusammenhang zwischen dem maximalen Torsionsmoment und der Verdrehungsdifferenz bei den vier Versuchen

Table 6 Correlation matrix (R) for the twelve studs showing the measured and calculated properties. E = dynamic modulus of elasticity (measured at 30%RH, 8%MC), G_{dyn} = dynamic modulus of shear (measured at 30% RH, 8% MC), ΔTW = the difference in free twist for the same difference in moisture content as the registered final M_T , M_T = the registered final torsional moment for a stud drying in restraint in in-service conditions, ρ = the density of the stud, SGA = the spiral grain angle on the tangential plane on the stud
Tabelle 6 Korrelationsmatrix (R) für die zwölf Holzständer mit den gemessenen und berechneten Parametern. E= dynamisches Elastizitätsmodul (bei 30% RH und 8% MC), G_{dyn} = dynamisches Schubmodul (bei 30% RH und 8% MC), ΔTW = Differenz der unbehinderten Verdrehung bezogen auf die dem maximalen Torsionsmoment entsprechende Feuchteänderung, M_T = maximales Torsionsmoment eines Holzständers, getrocknet im eingespannten Zustand unter Praxisbedingungen, ρ = Rohdichte, SGA = Faserwinkel in tangentialer Ebene gemessen

	M_T [Nm]	ΔTW [mm]	E [Mpa]	G_{dyn} [Mpa]	ρ [kg/m^3]	SGA [°]
M_T [Nm]	1.0	0.778	−0.185	−0.129	−0.309	−0.062
ΔTW [mm]		1.0	−0.367	−0.196	−0.323	−0.118
E [Mpa]			1.0	0.741	0.902	0.024
G_{dyn} [Mpa]				1.0	0.892	−0.070
ρ [kg/m^3]					1.0	0.001
SGA [°]						1.0

could explain the differences in the final M_T. The relationship between the measured material parameters and M_T can be seen in the correlation matrix in Table 6. The best correlation with the final M_T had a difference in free twist, ΔTW, $R = 0.78$. The correlation between the registered final M_T and any of the other material parameters was considerably weaker.

The spiral grain angle (SGA) shows a very poor correlation to the difference in free twist (ΔTW). Previous research has clearly shown a good correlation between SGA and ΔTW. About 40% ($R^2 = 0.40$) of the variation in twist has been shown to depend on the SGA, see Danborg (1994), for example. These twelve studs only resulted in $R = -0.118$, i.e. $R^2 = 0.014$. The poor correlation probably depended on the limited number of studs and the small variation in SGA.

There was only one pair of studs that was "matched" and came from the same log. They were EU26 and ET26. The difference in registered M_T, in free twist and SGA was small. However, the difference in terms of the modulus of elasticity and modulus of shear was fairly large. These moduli were measured using dynamic vibration methods. These two studs did not indicate that treatment such as top loading should affect the M_T.

Nor was there any indication that high-temperature drying affected the M_T. The two tested high-temperature-dried studs show results within the range of the other studs.

6 Discussion and concluding remarks

One of the objectives of this paper was to present the methodology that was used to measure M_T and the corresponding twist in in-service conditions. The method appears to have worked well. It was possible to obtain the M_T versus time and MC when drying in in-service conditions. However, the drying of timber and the development of M_T was very fast initially, after changing the RH in the surrounding air. This explains why the well-performed, rapid erection of the studs in the jig and the start of the registration were crucial. The erections in the test series were performed quickly and took less than one hour in each test series.

The results show a large variation in M_T between different studs, which is difficult to explain in full. The largest part of the development in M_T took place within two weeks when drying in in-service conditions (32% RH, equilibrium MC 8%) from 18% MC. The increase in M_T was very rapid during the first two weeks, even faster than the drying rate. This underlines the importance of retaining the MC in the timber at the target MC obtained during drying in a kiln. After about three months, the final M_T value was reached.

The magnitude of the final M_T ranged from 9.9 kNm to 41 kNm. A knowledge of the magnitude and development of M_T is important when designing the fasteners between elements in a timber structure.

The MC in the outer parts of a stud appears to have a greater impact on the development and magnitude of the M_T than the MC in the inner parts of the stud. This also shows that the outer parts have a greater impact on torsional stiffness than the inner parts.

Within the scope of this project, only twelve studs were tested. Further tests need to be conducted to obtain more statistically secure results and correlations. It would also be interesting to evaluate the influence of different dimensions and profiles, different distances to the pith, different spiral grain angles and the mechano-sorptive effect when restraining studs when cycling relative humidity.

Acknowledgement The authors would like to thank the sponsors that made this study possible: the SSF Wood Technology Programme, Södra skogsägarnas Foundation for Research, Development and Education, the EU "STRAIGHT" project (QLK5-2001-00276), the NTI, the Norwegian Institute of Technology, and the VTT Technical Research Centre of Finland.

References

Bäckström M, Johansson M, Kliger R (2004) Properties of timber converted by using novel techniques. Report on WP 5 STRAIGHT Project. Structural Engineering Mechanics – Steel and Timber Structures
Danborg F (1994) Drying Properties and Visual Grading of Juvenile Wood from Fast Grown Picea-Abies and Picea-Sitchensis. Scand J Forest Res 9(1):91–98
Johansson M, Perstorper M, Kliger R, Johansson R (2001) Distortion of Norway spruce timber – Part 2. Modelling twist. Holz Roh- Werkst 59:155–162
Kliger R, Johansson M, Perstorper M, Johansson G (2003) Distortion of Norway spruce – Part 3. Modelling bow and spring. Holz Roh- Werkst 61:241–250
Mackay JFG (1973) The influence of drying conditions and other factors on twist and torque in Pinus Radiata studs. Wood Fiber Sci 4(47):264–271

Northway RL (1981) Restraint forces needed to hold Radiata pine heart-in studs straight during high temperature drying. In: Proceedings of Forest Products Research Conference, CSIRO, Melbourne, Australia

Ormarsson S (1999) Numerical analysis of moisture related distortion in sawn timber. Doctoral thesis, Department of Structural Engineering, Chalmers University of Technology, Göteborg, Sweden

Perstorper M (1999) Dynamic testing of logs for prediction of timber strength. In: Proceedings of the Pacific Timber Engineering Conference, PTEC'99, Rotorua, New Zealand

Perstorper M, Johansson M, Kliger R, Johansson G (2001) Distortion of Norway spruce timber – Part 1. Variation of relevant wood properties. Holz Roh- Werkst 59:94–103

Salin JG (2004) STRAIGHT – Report on results obtained within Work-packages 2.4 and 2.7 Laboratory tests. SP-Trätek internal report, Stockholm, pp 1–32

Shmulsky R, Erickson RW (2004) Twist assessment and reduction in southern pine 2 by 4's. Forest Prod J 54(4):66–68